New search for T-violation in the decays of the charged kaon

V. Anisimovsky[*], **A. Ivashkin, Yu. Kudenko**

Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, 117312 Russia

(For the KEK-PS E246 Collaboration)

Abstract

We report the results of the measurement of T-violating transverse muon polarization in the decays $K^+ \to \mu^+\nu_\mu\pi^0$ ($K_{\mu3}$) and $K^+ \to \mu^+\nu_\mu\gamma$ ($K_{\mu2\gamma}$) performed in the experiment E246 at KEK. Preliminary results obtained for the entire data set taken in the period 1996-2000 are consistent with no T-violation in both decays.

1 Introduction

The purpose of the E246 experiment is to measure the transverse component of the muon polarization in the decay $K^+ \to \mu^+\nu_\mu\pi^0$ ($K_{\mu3}$), while we were also able to extract $K^+ \to \mu^+\nu_\mu\gamma$ ($K_{\mu2\gamma}$) decay as a by-product. The transverse muon polarization is a T-odd observable defined as $P_T = \vec{s}_\mu \cdot (\vec{p}_{\pi(\gamma)} \times \vec{p}_\mu)/|\vec{p}_{\pi(\gamma)} \times \vec{p}_\mu|$ where $\vec{p}_\pi$ is used for $K_{\mu3}$ and $\vec{p}_\gamma$ for $K_{\mu2\gamma}$, respectively.

In the framework of the phenomenological consideration, the transverse muon polarization can be related to the $K_{\mu3}$ and $K_{\mu2\gamma}$ form factors. For $K_{\mu3}$ the T-violating polarization is proportional to the imaginary part of the ratio

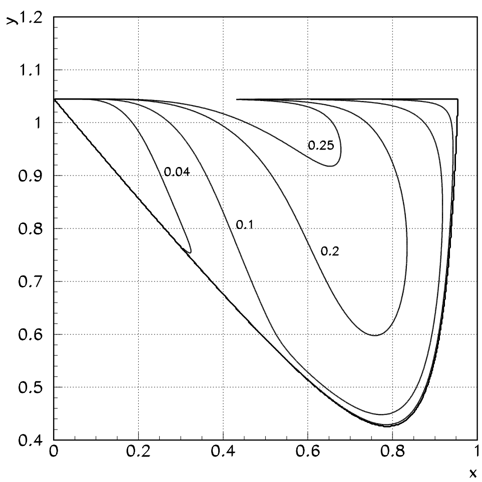
[*]E-mail: valera@al20.inr.troitsk.ru

of $K_{\mu 3}$ form factors: $P_T \propto m_\mu m_K \mathrm{Im}(\xi)$, where $\xi = f^-/f^+$ and f^+, f^- are defined through

$$M_{K_{\mu 3}} \sim G_F \sin\theta_c \left[f^+(q^2)(p_K^\lambda + p_\pi^\lambda) + f^-(q^2)(p_K^\lambda - p_\pi^\lambda) \right] \cdot [\bar{u}_\mu \gamma_\lambda (1-\gamma_5) u_\nu]$$

The Standard Model predicts a vanishing value of less than 10^{-7} for P_T in $K_{\mu 3}$ [1]. The calculations of P_T due to the electromagnetic final state interactions result in a value of less than 10^{-5} [2]. There are several non-standard models predicting sizeable value for P_T: multi-Higgs models, SUSY with squarks mixing, SUSY with R-parity violation, leptoquark models [3, 4]. The values predicted in these models vary from 4×10^{-4} to 10^{-2}.

In case of $K_{\mu 2\gamma}$ the transverse polarization is related to the decay form factors in a more complicated way: $P_T(x,y) = \sigma_V(x,y)\mathrm{Im}(\Delta_V + \Delta_A) + [\sigma_V(x,y) - \sigma_A(x,y)]\mathrm{Im}(\Delta_P)$ where $\sigma_V(x,y)$ and $[\sigma_V(x,y) - \sigma_A(x,y)]$ are the functions of $K_{\mu 2\gamma}$ kinematic parameters (shown in Fig. 1), and $\Delta_{(V,A,P)}$ are the contribu-



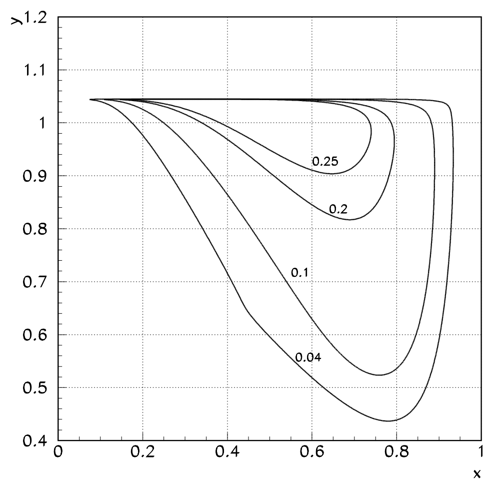


Figure 1: The contour lines of $[\sigma_V(x,y)]$ (left) and $[\sigma_V(x,y) - \sigma_A(x,y)]$ (right) over the Dalitz plot. The standard $K_{\mu 2\gamma}$ kinematic variables $x = \frac{2E_\gamma}{m_K}$ and $y = \frac{2E_\mu}{m_K}$.

tions of non-standard interactions to the effective form factors [5]. Although the Standard Model prediction for P_T in $K_{\mu 2\gamma}$ is as small as for $K_{\mu 3}$ [1], the contribution of the final state interaction to this value is $\leq 10^{-3}$ [6], i.e. considerably larger than in the case of $K_{\mu 3}$ decay. The predictions for non-zero

P_T for $K_{\mu 2\gamma}$ come from the same non-standard models mentioned for $K_{\mu 3}$ and also from left-right symmetric models [4, 5, 7]. The expected values vary from 3×10^{-3} to 10^{-2}.

The noteworthy peculiarity of these predictions obtained in different models is the correlations between the expected values of P_T for $K_{\mu 3}$ and $K_{\mu 2\gamma}$ [3, 4, 7]: in the three Higgs doublet model the P_T expectations are related as $P_T(K_{\mu 3}) \sim 2P_T(K_{\mu 2\gamma})$; in SUSY with squarks mixing the relation for P_T induced by Higgs exchange: $P_T(K_{\mu 3}) \sim -2P_T(K_{\mu 2\gamma})$, while for P_T arising from W-boson exchange: $P_T(K_{\mu 3}) \sim 0$, $P_T(K_{\mu 2\gamma}) \neq 0$; in SUSY with R-parity violation the relation is $P_T(K_{\mu 3}) \sim P_T(K_{\mu 2\gamma})$; in left-right symmetric models we have: $P_T(K_{\mu 3}) = 0$, $P_T(K_{\mu 2\gamma}) \neq 0$.

The previous experimental results for $K_{\mu 3}$ came from the BNL experiment which used kaon decays in flight [8]: $P_T = (-3.1 \pm 5.3) \times 10^{-3}$, $\mathrm{Im}(\xi) = (-1.6 \pm 2.5) \times 10^{-2}$, as well as from E246 [9]: the result obtained for the data collected during 1996-1997 period was $P_T = (-4.2 \pm 4.9(stat) \pm 0.9(syst)) \times 10^{-3}$, $\mathrm{Im}(\xi) = (-1.3 \pm 1.6(stat) \pm 0.3(syst)) \times 10^{-2}$. Both results indicated no T-violation in $K_{\mu 3}$. For $K_{\mu 2\gamma}$ there has been no P_T measurement, so our result is the first one.

2 Experiment

The E246 apparatus is shown in Fig. 2, and described in detail elsewhere [10].

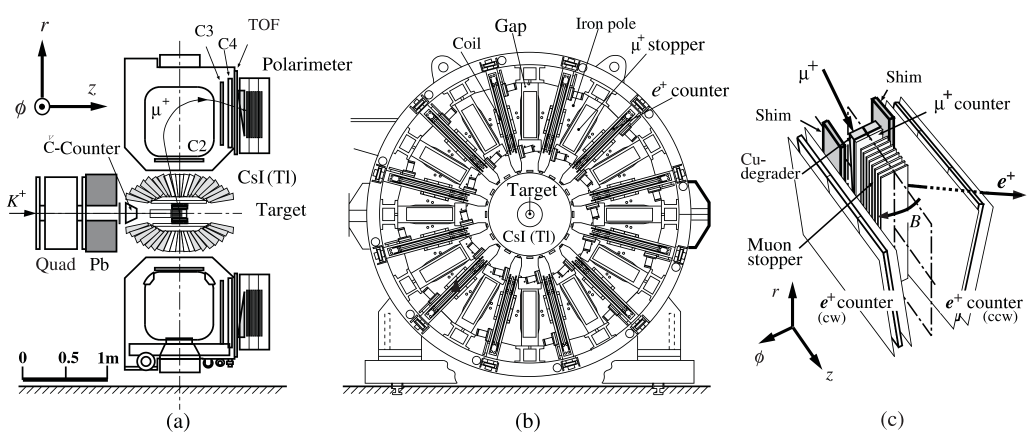


Figure 2: The layout of the E246 detector: (a) side view, (b) end view and (c) one sector of the polarimeter.

Kaons with $P_{K^+} = 660$ MeV/c are identified by a Čerenkov counter, slowed in an Al+BeO degrader and then stopped in a target array of 256 scintillating fibers located at the center of a 12-sector superconducting toroidal spectrometer. Charged particles from kaon decays in the target were tracked by means of multi-wire proportional chambers at the entrance (C2) and exit (C3 and C4) of each magnet sector, along with the target and a scintillation ring hodoscope around the target. The momentum resolution of $\sigma_p = 2.6$ MeV/c at p=205 MeV/c was obtained using mono-energetic products from the two-body decay $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$). The energies and angles of the photons from π^0 decays were measured by a CsI(Tl) photon detector consisting of 768 modules. The photon detector covers a solid angle of 3π steradian, with openings for the beam entry and exit and 12 holes for charged particles to pass into the magnet gaps. To suppress accidental background from the beam, timing information from each crystal was used. A good time resolution of 3.5 nsec (rms) at 100 MeV was achieved. Energy resolution of $\sigma_E/E = 2.7\%$ at 200 MeV, angular resolutions of $\sigma_\theta = 2.3°$ and the invariant mass resolution of $\sigma_{\gamma\gamma} = 9$ MeV/c^2 were obtained. Muons entering the polarimeter (Fig. 2c) were degraded by an Al+Cu block and stopped in a stack of pure Al plates. Positrons from $\mu^+ \to e^+\nu\bar{\nu}$ decays of stopped muons were detected by positron counters which were located azimuthally between the muon stoppers.

The trigger included the signals from Čerenkov, target, TOF and positron counters along with the requirement of at least one hit in CsI(Tl) calorimeter.

The T-violating asymmetry was extracted using a double ratio as:

$$A_T = \frac{1}{4}\left[\frac{(N_{cw}/N_{ccw})_{fwd}}{(N_{cw}/N_{ccw})_{bwd}} - 1\right]$$

Here, N_{cw} and N_{ccw} are the sums over all 12 sectors of counts of clockwise (cw) and counter-clockwise (ccw) emitted positrons and fwd/bwd denote events with the photon (or π^0) going forward/backward with respect to beam direction. The sign of A_T for fwd events is opposite to that of bwd events that allows us to employ a double ratio method which reduces most systematic errors and enhances the effect. Moreover, considerable reduction of systematic effects was achieved due to the azimuthal symmetry of the 12-sector detector.

The value of P_T is related to A_T by

$$P_T = \frac{A_T}{\alpha \times f \times (1-\beta)}$$

where α is the analyzing power of the polarimeter, f is an angular attenuation factor and β is the overall fraction of backgrounds.

3 Analysis

The extraction and analysis of $K_{\mu3}$ and $K_{\mu2\gamma}$ events comprised several procedures common for both decays. The common stage included target analysis, charged particle tracking and TOF analysis and the analysis of muon decay in polarimeter. Active target analysis included target energy deposition and target timing cuts to get rid of kaon decays in flight. The momentum of charged particle reconstructed by four-point tracking procedure was used to suppress $K_{\mu2}$ and $K_{\pi2}$ decays by selecting events with $p < 190$ MeV/c. The cut on χ^2 for the charged particle track was used to suppress $K_{\pi2}$ decays with π^+ decay in flight. To separate muons and positrons (thereby suppressing K_{e3}) we used time-of-flight (TOF) technique to calculate charged particle mass and then, on the scatter plot of the TOF energy deposition versus TOF-reconstructed mass square, we separated the muon cloud from the positron one. Finally, the common stage included the signal extraction from the positron time spectra in the polarimeter.

The second stage of event selection was specific for each decay mode. For $K_{\mu3}$ we selected one-photon events with $E_\gamma > 70$ MeV and two-photon events which satisfy the constraints on the invariant mass of the two photons and on the missing mass (reconstructed mass of missing neutrino): $70 < M_{\gamma\gamma} < 180$ MeV/c^2 and $-25000 < M^2_{miss} < 20000$ MeV^2/c^4. Additionally, we used the cuts on the opening angles between two photons and between muon and π^0: $\Theta_{\gamma\gamma} > 60°$ and $\Theta_{\mu\pi} < 160°$ to suppress kaon decays in flight and $K_{\pi2}$.

The second stage for $K_{\mu2\gamma}$ selected one-photon events with $E_\gamma > 50$ MeV and comprised three major cuts: a constraint on the neutrino missing mass $-0.7 \times 10^4 < M^2_{miss} < 1.5 \times 10^4$ MeV^2/c^4, a cut on the neutrino momentum $p_\nu > 200$ MeV/c and a cut on the opening angle between muon and photon $\Theta_{\mu\gamma} < 90°$. These cuts suppressed the $K_{\mu3}$ by a factor of 70, while sustaining a $K_{\mu2\gamma}$ loss by a factor of 2. Fig. 3 shows the spectra of M^2_{miss} and p_ν for both Monte Carlo (MC) ($K_{\mu3}$ and $K_{\mu2\gamma}$) and experimental data.

The background fractions for extracted $K_{\mu3}$ and $K_{\mu2\gamma}$ events were estimated using experimental spectra along with the MC simulation data. For $K_{\mu3}$ the major background contributions come from CsI(Tl) accidental hits, K_{e3} and $K_{\pi2}$. All these backgrounds do not induce spurious asymmetry and

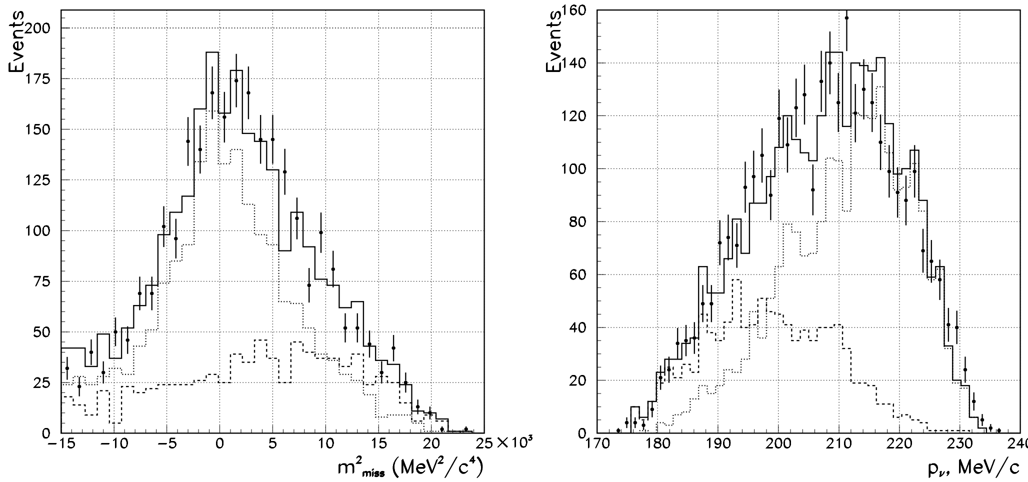


Figure 3: The spectra of the neutrino missing mass (left) and momentum (right) for $K_{\mu 2\gamma}$ selection. The black dots with error bars show the experimental data. MC simulation: dotted line – $K_{\mu 2\gamma}$, dashed line – $K_{\mu 3}$, solid line – $K_{\mu 2\gamma} + K_{\mu 3}$.

only dilute the sensitivity to P_T. The total background fraction for $K_{\mu 3}$ was estimated to be $\leq 16.0\%$.

In the case of $K_{\mu 2\gamma}$ the situation is much worse due to the predominant background of $K_{\mu 3}$ events with one photon escaping CsI(Tl) detector. Such events almost completely mimic $K_{\mu 2\gamma}$ kinematics, so they cannot be suppressed without a considerable loss of useful $K_{\mu 2\gamma}$ events. The optimized $K_{\mu 2\gamma}$ cuts reduced the background fraction from $K_{\mu 3}$ to about 17%. The background $K_{\mu 3}$ events might have non-zero P_T thereby inducing spurious transverse asymmetry. Fortunately, we measure P_T in $K_{\mu 3}$ with higher sensitivity in the same experiment and can reliably estimate this effect. Therefore, we can safely assume no spurious contribution to P_T from $K_{\mu 3}$ background. The second major source of background is accidental photons in the CsI(Tl) detector. It was suppressed to the level of $\leq 8\%$ by requiring a photon energy threshold of 50 MeV and a coincidence between a signal from charged particle and a photon signal in the CsI within a window ± 15 ns. Other background modes are suppressed by the $K_{\mu 2\gamma}$-specific cuts to a negligible level. The total background fraction for $K_{\mu 2\gamma}$ sample was estimated to be $\leq 25\%$.

The valuable part of the asymmetry analysis includes the extraction of the value of the normal asymmetry A_N which is proportional to the T-even muon polarization, i.e. the in-plane component of the muon polarization normal to the muon momentum. It can be measured by selecting events with π^0 (or photon for $K_{\mu 2\gamma}$) moving into the left or right hemisphere with respect to the median plane of the given magnet sector. The theoretical calculations indicate that the normal polarizations for $K_{\mu 3}$ [11] and $K_{\mu 2\gamma}$ [5] have opposite signs for the kinematic region where selected events are located, as shown in Fig. 4. For

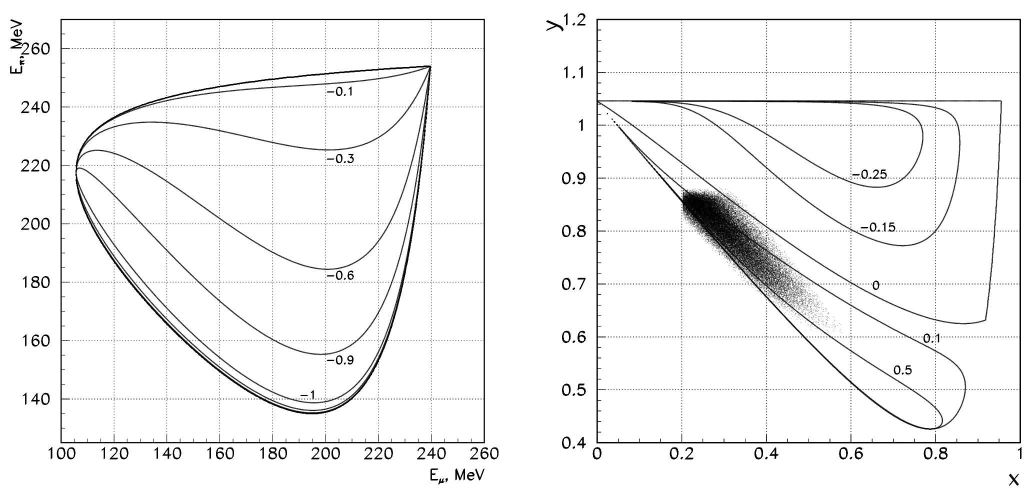


Figure 4: Contour lines of the normal polarization over the Dalitz plot: $K_{\mu 3}$ (left) and $K_{\mu 2\gamma}$ (right). The dots represent the $K_{\mu 2\gamma}$ experimental data.

one-photon $K_{\mu 3}$ events, we obtained $A_N(K_{\mu 3}(1\gamma)) = (-3.87 \pm 0.06) \times 10^{-2}$ while for $K_{\mu 2\gamma}$ we have $A_N(K_{\mu 2\gamma}) = (+3.67 \pm 0.44) \times 10^{-2}$. This gives us a robust evidence of the sufficiently pure $K_{\mu 3}$ and $K_{\mu 2\gamma}$ selection. The study of the dependence of the normal asymmetry on the energy of π^0 shows a sound agreement with the theoretical calculation. By comparing the values of the normal asymmetry and normal polarization obtained using Monte Carlo simulation using the relation $A_N = \alpha \times P_N$, we are able to extract the value of the polarimeter analyzing power $\alpha = 0.289 \pm 0.015$.

The main systematic uncertainties in P_T come from magnetic field rotation, detector components misalignment, CsI(Tl) accidental background, beam profile asymmetry and decay plane rotation. The important point is

that the sources of systematics are mostly the same for both measured decays, so we can estimate the systematic contributions using a large sample of $K_{\mu3}$ data and then use the same error value for $K_{\mu2\gamma}$. Most of the systematic effects are canceled by the unique features of the set-up (azimuthal symmetry, double ratio, etc). We evaluated the contributions from all relevant sources using the MC simulation data and comparing them with the experimental distributions [9]. Overall systematic error was estimated to be $\delta P_T = 0.92 \times 10^{-3}$ which is well below the level of the statistical error.

4 Results

After the analysis of the entire data set collected in the period 1996-2000 we obtained the results for both $K_{\mu3}$ and $K_{\mu2\gamma}$. For $K_{\mu3}$ we selected 6.3×10^6 one- and two-photon forward/backward events and using the angular attenuation factor value extracted from MC simulation ($f = 0.72 \div 0.77$ for 2γ events and $f = 0.56 \div 0.66$ for 1γ events) the preliminary result $P_T = (-1.12 \pm 2.17(stat) \pm 0.92(syst)) \times 10^{-3}$ is obtained. Using the relation $P_T = \mathrm{Im}(\xi)\cdot\Phi$ (where Φ is a kinematic factor, evaluated from MC simulation $\Phi \sim 0.2 \div 0.3$) we get $\mathrm{Im}(\xi) = (-0.28\pm0.69(stat)\pm0.30(syst))\times10^{-2}$ [12]. The dependences of the transverse asymmetry on the beam cycle, π^0 energy and magnet sector number indicate no systematic irregularity and thus confirm the robustness of our systematics study. The results indicate no evidence of T-violation in $K_{\mu3}$ and can be interpreted as limits on the measured quantities: $|P_T| < 4.3\times10^{-3}$ at 90% c.l. and $|\mathrm{Im}(\xi)| < 1.3 \times 10^{-2}$ at 90% c.l.

We have performed the first measurement of P_T in the $K_{\mu2\gamma}$ decay (it is also the first $K_{\mu2\gamma}$ measurement below $K_{\pi2}$ peak). The result obtained for 1996-1998 data was published in [13]. Here we present the result of the analysis of the whole data set of 1.88×10^5 forward/backward events. We obtained the value $P_T = (-0.14 \pm 1.44(stat) \pm 0.10(syst)) \times 10^{-2}$ with the evaluated attenuation factor of $f = 0.80 \pm 0.03$. Similarly to the case of $K_{\mu3}$, we see no indication of T-violation in this decay and we can put the limit $|P_T| < 2.4 \times 10^{-2}$ (90% c.l.)

5 Conclusion

We have performed the new measurement of T-violating muon polarization in two decays $K_{\mu3}$ and $K_{\mu2\gamma}$ for which several non-standard models predict non-zero P_T values. For $K_{\mu2\gamma}$ decay our result is the first one. At the current level of the experimental sensitivity, we see no evidence for T-violation and our results allowed us to impose constraints on several non-standard models: three Higgs doublet model (the most stringent experimental constraint), SUSY with squark mixing, SUSY with R-parity violation, leptoquark models, left-right symmetric models (see, for example, Ref. [14]). Much higher statistical sensitivity to P_T of $\leq 10^{-4}$ can be reached in a proposed experiment [15] at the high intensity low energy separated kaon beam at J-PARC [16]. In addition, the P_N values in $K_{\mu3}$ and $K_{\mu2\gamma}$ can be measured with high accuracy in this experiment that provides a new sensitive method for determination of the kaon form factor values in these decays [17].

References

[1] E. Golowich and G. Valencia, Phys. Rev. D **40**, 112 (1989); I. I. Bigi and A. I. Sanda, Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. **9**, 1 (2000).

[2] A. R. Zhitnitsky, Sov. J. Nucl. Phys. **31** (1980) 529 [Yad. Fiz. **31** (1980) 1024]; V. P. Efrosinin *et al.*, Phys. Lett. B **493**, 293 (2000) [arXiv:hep-ph/0008199].

[3] C. Q. Geng and S. K. Lee, Phys. Rev. D **51**, 99 (1995); G. H. Wu and J. N. Ng, Phys. Lett. B **392**, 93 (1997); M. Fabbrichesi and F. Vissani, Phys. Rev. D **55**, 5334 (1997); G. Belanger and C. Q. Geng, Phys. Rev. D **44**, 2789 (1991).

[4] M. Kobayashi, T. T. Lin and Y. Okada, Prog. Theor. Phys. **95**, 361 (1996) [arXiv:hep-ph/9507225].

[5] C. H. Chen, C. Q. Geng and C. C. Lih, Phys. Rev. D **56**, 6856 (1997)

[6] V. V. Braguta *et al.*, Phys. Rev. D **66**, 034012 (2002) [arXiv:hep-ph/0205203].

[7] G. H. Wu and J. N. Ng, Phys. Rev. D **55**, 2806 (1997) [arXiv:hep-ph/9610533].

[8] S. R. Blatt *et al.*, Phys. Rev. D **27** (1983) 1056.

[9] M. Abe *et al.* [KEK-E246 Collaboration], Phys. Rev. Lett. **83**, 4253 (1999); M. Abe *et al.* [KEK-E246 Collaboration], Nucl. Phys. A **663** (2000) 919.

[10] M. Abe *et al.* [E246 KEK PS Collaboration], Nucl. Instrum. Meth. A **506**, 60 (2003)

[11] N. Cabibbo and A. Maksymowicz, Phys. Lett. **9** (1964) 352; Errata ibid., **11** (1964) 360; Errata ibid.,**14** (1965) 72.

[12] M. Abe *et al.* [KEK-E246 Collaboration], Nucl. Phys. A **721**, 445 (2003) [arXiv:hep-ex/0211049].

[13] V. V. Anisimovsky *et al.* [KEK-PS E246 Collaboration], Phys. Lett. B **562**, 166 (2003).

[14] F. L. Bezrukov, D. S. Gorbunov and Y. G. Kudenko, Eur. Phys. J. C **30** (2003) 487 [arXiv:hep-ph/0304146].

[15] Y. G. Kudenko and A. N. Khotyantsev, Phys. Atom. Nucl. **63**, 820 (2000) [Yad. Fiz. **63**, 890 (2000)];

[16] Proceedings of the International Workshop on JHF Science, eds. J. Chiba, M. Furusaka, H. Miyatake and S. Sawada, V. I-III, KEK Proceedings 98-5, August 1998.

[17] F. L. Bezrukov, D. S. Gorbunov and Y. G. Kudenko, Phys. Rev. D **67**, 091503 (2003) [arXiv:hep-ph/0302106].